

"The Effects of Changes of Temperature on the Modulus of Torsional Rigidity of Metal Wires." By FRANK HORTON, D.Sc., B.A., St. John's College, Cambridge; 1851 Exhibition Research Scholar of the University of Birmingham. Communicated by Professor J. J. THOMSON, F.R.S. Received March 17,—Read April 28, 1904.

(Abstract.)

This paper contains an account of some experiments performed with the object of ascertaining, as accurately as possible, the manner in which the modulus of torsional rigidity varies with the temperature. The law governing this variation has been expressed in several different forms by those who have investigated it, but all the more recent experimenters have been content with finding the modulus at two temperatures only and assuming a linear law to hold between them. The first part of the paper contains a short account of the results obtained by previous investigators, and possible sources of error in the methods employed are pointed out. The rest of the paper is divided into the following sections:—

- (1) Description of apparatus, etc.
- (2) Account of the experiments.
- (3) Summary of results and comparison with those of other observers.
- (4) Determination of the coefficients of expansion of the wires.

The metals experimented on were copper, iron, platinum, gold, silver, aluminium, tin, lead, cadmium, all chemically pure, and also specimens of commercial copper and of steel pianoforte wire. The wire used were of approximately the same length and diameter, and were carefully annealed before the rigidity determinations were begun.

The method of experimenting employed was a dynamical one, the torsional oscillations of the wire under test being timed by a method of coincidences capable of great exactness. Some of the observations made in the course of this work yielded what seemed to be interesting information as to the internal viscosities of the wires used. This is recorded in the paper and compared with similar observations by other experimenters.

The vibrator generally used was a circular disc of gunmetal, and this was completely enclosed with the wire in a heating jacket, the temperature of which could be varied as required. Observations of the period of torsional vibration were made, in general, at five temperatures, viz., at the temperature of the room, about 16° C., at 35° C., 55° C., 75° C., and 100° C., and also in some cases at 126° C., the higher temperatures being obtained by using the vapours of various liquids boiling under atmospheric pressure.

The method of coincidences used in timing the torsional vibrations consists in observing the reflections of a vertical flash occurring once a second, in two mirrors, one of which is fixed in position, and the other is attached to the vibrator and vibrates with it, swinging just above the fixed mirror and being parallel to it when at rest. The reflections are observed by means of a telescope, in the field of view of which, in general, two flashes are seen, one always occurring in the same position, and the other appearing in different parts of the field according to the position of the moving mirror at the instant the flash occurs. If a second signal happens exactly when the two mirrors are parallel, the two flashes coincide, and it is from these "coincidences" that the time of vibration is obtained. The method of coincidences is usually only applied to the comparison of two nearly equal times, but it is shown in the paper to be equally applicable to any two periods even if they are quite different.

In order that the observed periods at different temperatures may be comparable, it is necessary that they should be corrected for the increased length and radius of the wire, and also for the expansion of the vibrator at higher temperatures. For this purpose the coefficients of expansion of the wires, and of a gunmetal bar cast at the same time as the vibrator, were determined by means of the measuring bench in the Physical Laboratory of the University of Birmingham, which Professor Poynting kindly placed at my disposal. A description of the instrument (which has not otherwise been described), and the results of the experiments, are given in Part 4 of the paper.

In addition to the determination of the periods of vibration, observations of the logarithmic decrement of the amplitudes of the oscillations were taken at each temperature, and thus the effect of temperature on the internal viscosity of the wires was observed. At the end of the rigidity determinations for each wire, a series of observations was usually taken to ascertain the manner in which the logarithmic decrement and the torsional period varied with the amplitude of vibration, amplitudes up to about  $10^\circ$  being used. The main observations for the rigidity determinations were all taken at the constant average amplitude of  $14'$ .

The following is a summary of the principal results :—

1. In all the materials examined, with the exception of pure copper and of steel, the modulus of rigidity at one temperature is not constant, but increases as time goes on. The rate of increase of rigidity with time is greater the higher the temperature, and repeated heatings to the same temperature gradually lessen the rate of alteration with time at that temperature, but even in the course of months of experimenting the increase of rigidity with time cannot be entirely eliminated.

2. The diminution of the modulus of rigidity per degree rise of

temperature between  $10^{\circ}\text{C.}$  and  $100^{\circ}\text{C.}$  is constant for pure copper and for steel, but not for any of the other materials examined.

3. In the case of the metals iron, gold, tin, lead and commercial copper, the rigidity temperature curve is of such shape as to suggest that if it were possible to obtain the values of the rigidity modulus at the different temperatures, all within a very short space of time (so as to avoid the "time effect"), the resulting curve would be a straight line.

4. In the case of the metals platinum, silver, aluminium, the shape of the rigidity-temperature curve shows that the effect of the gradual increase of rigidity with time is such as to make the alteration with temperature approximate more closely to a linear law than would be the case if the observations were all taken within a very small interval of time. For these metals, therefore, the decrease of torsional elasticity per  $1^{\circ}\text{C.}$  rise of temperature increases with the temperature.

5. In general, the effect of heating to a high temperature is to increase the value of the rigidity modulus at lower temperatures. (This applies even to pure copper, of which the modulus of rigidity at the ordinary laboratory temperature is slightly greater after the wire has been heated to higher temperatures. The rigidity of steel was quite constant, and with silver the value of the modulus at the temperature of the laboratory in the last few experiments was unaltered by a temporary increase of temperature. Tin was the only case in which the rigidity modulus at the ordinary laboratory temperature was lessened by heating.)

6. The internal viscosity of all the metals examined, with the exceptions of soft iron and steel, increases with the temperature. This increase varies very much with different metals, being greatest with aluminium and least with platinum. The internal viscosity of soft iron decreases rapidly with rise of temperature and reaches a minimum value at about  $100^{\circ}\text{C.}$  There is a slight decrease also in the case of steel.

7. Repeated heating and continued oscillation through small amplitudes decrease the internal friction.

8. Both the internal friction and the period of torsional vibration increase with the amplitude of oscillation. The increase is generally greater the higher the temperature of the wire. It is least in the case of steel and is small in the case of soft iron.

9. Vibration through a large amplitude considerably alters both the logarithmic decrement and period of oscillation at smaller amplitudes. The nature of the alteration varies with different metals, being in some cases an increase and in some a decrease.

10. The internal viscosity of a well-annealed wire suspended and left to itself gradually decreases.

11. The internal viscosity of an unannealed wire is enormously reduced by annealing.

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